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DOE/NRC Analysis of Fukushima Accident Using MELCOR 2.1

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Randall Gauntt
Sandia National Laboratories
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Participants in Study

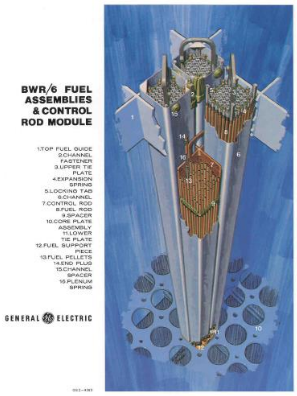
- DOE/NRC
  - Damien Peko and Richard Lee
- Sandia – MELCOR 2.1 Analyses of Accidents and SFP-4
  - Randy Gauntt, Donald Kalinich, Jeff Cardoni, Jesse Phillips, Andrew Goldmann, Susan Pickering
- INL – Fukushima Data Portal
  - Curtis Smith, Shawn St. Germain, David Schwieder, Cherie Phelan
- ORNL – MELCOR 1.8.5 Analysis of Unit 3 and HPCI, SFP-4
  - Matthew Francis, Kevin Robb, Larry Ott, Dean Wang
- Technical Reviews
  - TEPCO, JNES, DOE, NRC, EPRI and notable experts
- *http://melcor.sandia.gov/Fukushima_SAND_Report_final.pdf*

Topics for discussion

- BWR Overview
- Severe Accident Analysis
- Modeling RCS/Containment Failure Mechanisms
- The accidents
- Future Activities
- Conclusions

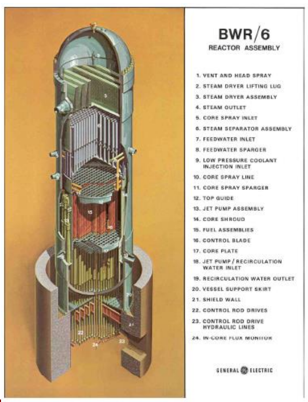
BWR Fuel

- Fuel rods
- Channel boxes
- Control blade
- Core plate
- Fuel support pieces



BWR Vessel

- Lower Plenum
- Core
- Steam separators
- Steam dryers
- Steam dome

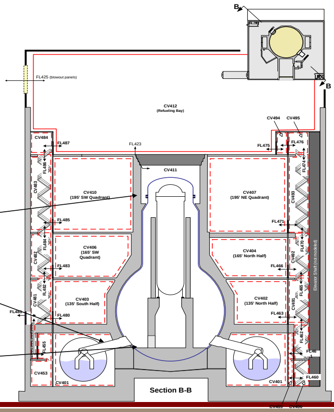


Mark-I Containment

NRC Training Manual

Browns Ferry from Wikipedia

MELCOR Model of Reactor Building



Drywell head flange failure location

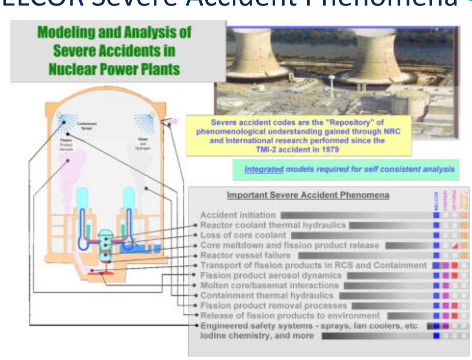
DW Vent bellows not modeled

Drywell liner failure location

Key Safety Systems also Modeled

- Safety relief valves
  - Cycle open and closed to limit RPV pressure
  - Vent steam and decay energy into suppression pool
- Isolation condensers (Unit 1)
  - Rejects heat to water tanks
  - Valves must be open and tanks must be refilled after ~8 hours
- RCIC (Unit 2 and 3) and HPCI (Unit 3) turbine-driven water injection into RPV
  - Condensate storage tanks
  - Recirculation of Torus water
  - Turbine exhausts steam and decay heat into suppression pools
- RHR system – moves heat from suppression pool to ocean
  - Since RHR pumps were flooded, heat rejection to ocean was not possible

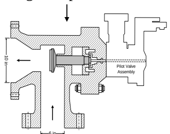
MELCOR Severe Accident Phenomena

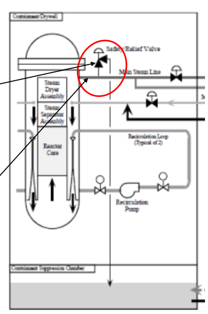


COMPONENT FAILURE MODELING IN MELCOR

Means of Vessel Depressurization

Seizure of SRV from excessive cycles at high temperature

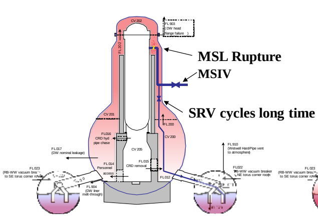


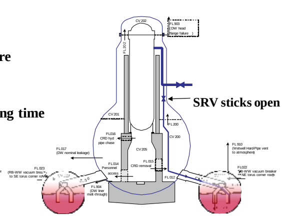


Or,

Rupture of main steam line for cycling SRV

SRV Seizure Versus MSL Rupture





Main Steam Line Rupture vents Fission products to drywell

Release to environment via head Flange failure or drywell liner melt through

SRV Seizure vents fission products Into wetwell

Wetwell scrubbing prevents release To the environment

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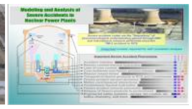

The Accidents

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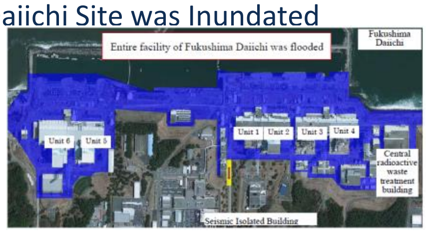
Earthquake Led to Loss of Offsite Power

- Seismic events disrupted roads and power lines
- Regional blackout isolated Fukushima station from power grid
- Reactors shut down
- Site operated by onsite diesel generators

Circuit Breaker damaged

Collapsed tower

Daiichi Site was Inundated

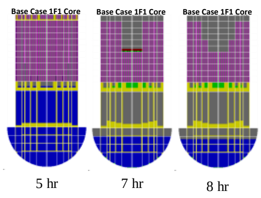


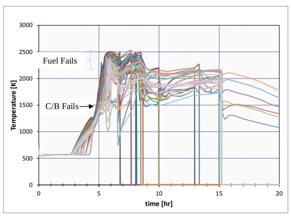
Used by permission from TEPCO

- Site flooding initiated "Station Blackout"
  - Diesel generators flooded and fuel tanks swept away
- Unit 2 and 3 maintained "Emergency Core Cooling System"
  - DC power available
- Unit 1 also lost DC batteries
  - blind to what was happening and No ECCS
- All reactors isolated from ultimate heat sink (Ocean)

UNIT 1 ANALYSIS

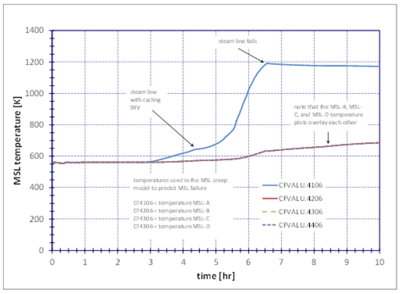
Initial Core Heatup and Degradation





- Core damage starts at ~ 4 hours – Control Blade fails first
- Progressive fuel damage after 6 hours
- Core exit gas temperatures very high

High Gas Temperature Weakens Steam Line



- Zr oxidation produces hydrogen and high gas temperature
- Cycling SRV vents hot gas through steam line and into suppression pool
- High RPV pressure ruptures weakened steam line
- TEPCO favors gasket blowout theory
- *SRV failure by seizing open is completely plausible alternative*
  - *Subsequent SA progression not strongly affected*

Progressive Core Degradation

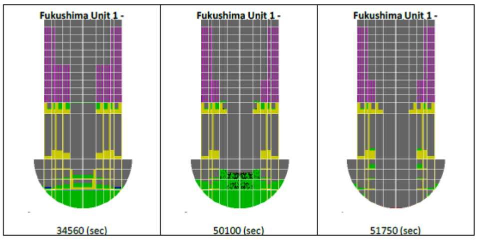


Figure 39 MELCOR-predicted core damage state near time of lower head failure - note some intact fuel assemblies remain in the core region.

- MCCI experiment
- Decay heat liberates water from concrete
- Metals (Zr and steel) oxidize and produce H_2 and CO
- Exothermic energy from chemical reactions

RSC: 1/02

Drywell Pressure

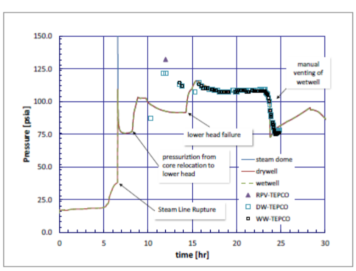
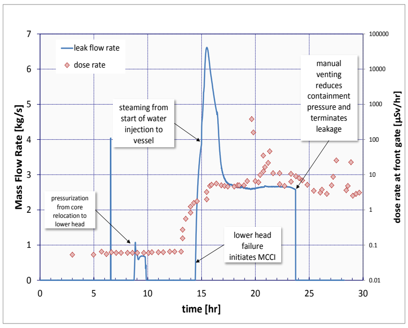


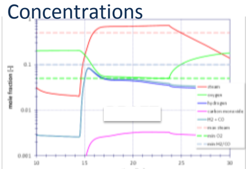
Figure 44 MELCOR-predicted containment pressure during the MCCI gas generation phase up to the point of manual containment venting.

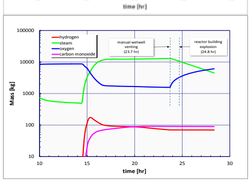
Dry Well Head Flange Leakage



- Flange leakage driven by MCCI gas generation and by steam from water injection
- Idealized flange leakage model closes leak path when manual venting lowers PCV pressure
- Also, water injection is suspended just prior to venting
- Stops (or slows) steam/gas leak to refueling bay

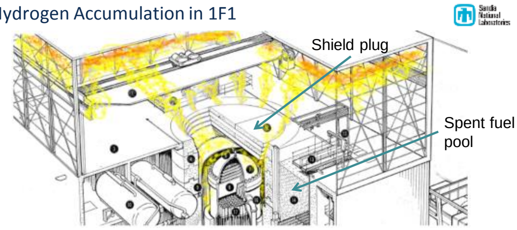
Unit 1 Results - Refueling Bay Vapor/Gas Molar Concentrations





- Steam, H_2, and CO enter the refueling bay via the drywell head flange leakage (drywell head lifts due to high containment pressure).
  - Persists for ~10 hours
- O_2 concentration decreases as air is displaced by steam H_2 and CO.
- Wetwell is vented at ~24 hr; containment pressure drops and drywell head reseats.
  - *Water injection also stopped*
- Steam concentration decreases and O_2 increases as steam condenses and air ingress commences
- Well-mixed volume concentrations are slightly below the minimum H_2/CO flammability limit
  - total of 900 kg vented into the refueling bay, but only 100 to 200 kg resident at any given time.
- *Thermally buoyant plume of H_2/steam rising to ceiling not modeled*
- *Light gas (H_2) stratification not modeled*

Hydrogen Accumulation in 1F1



- Between ~12 hours and ~23 hours, steam and hydrogen leaks from drywell head flange and enters RB via shield plug seams
- Hydrogen, CO and steam rises to roof and spreads laterally
- Steam produced in MCCI and from emergency water injection
- Condensation in refueling bay depletes steam in hot layer and enriches hydrogen
- Mixture displaces air from building
- Steam mole fraction exceeds 50% - inert conditions prevent combustion

Combustible Conditions Follow PCV Venting in 1F1

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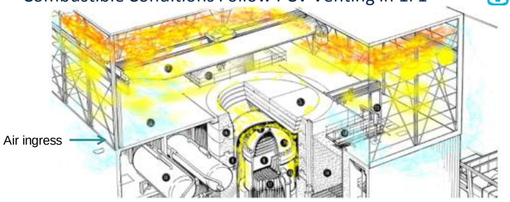

- At around ~23 hours, steam and hydrogen leakage from PCV greatly reduced
  - Water injection was stopped
  - PCV was depressurized by operator venting action
- Continuing condensation without steam source….
  - Reduces steam molar fraction to below 50% in refueling bay, and
  - Produces partial vacuum that draws in outside air
- Air ingress and steam condensation leads to conditions favoring combustion
- Hydrogen stratification produces flammable or detonable concentrations of H_2/O_2

Damage from Explosions

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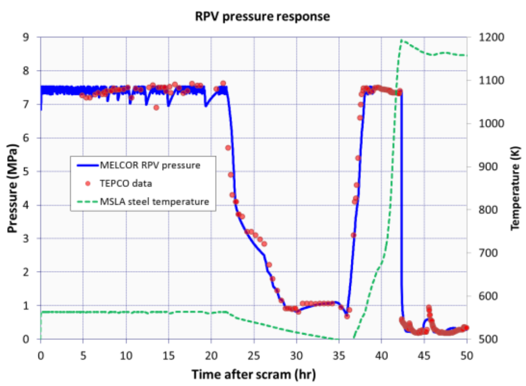
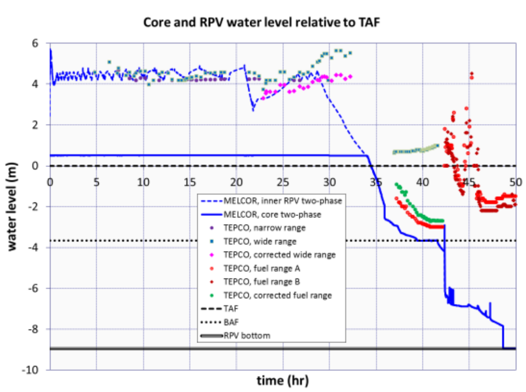
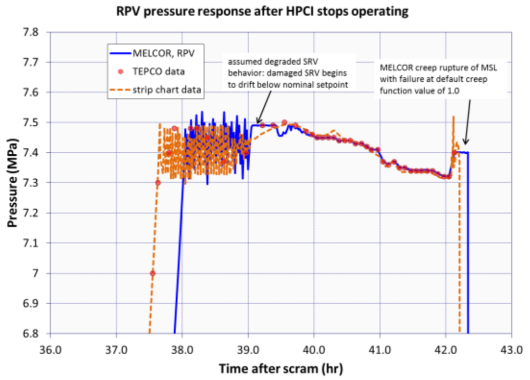
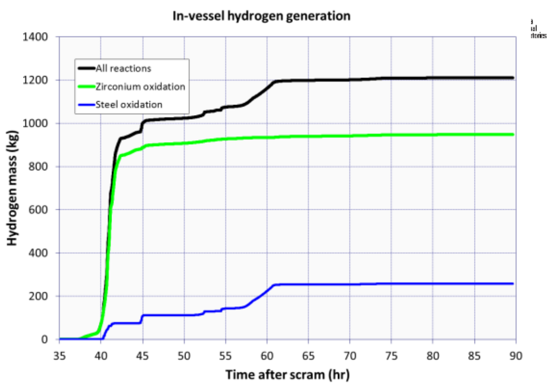
UNIT 2 ANALYSIS ONGOING

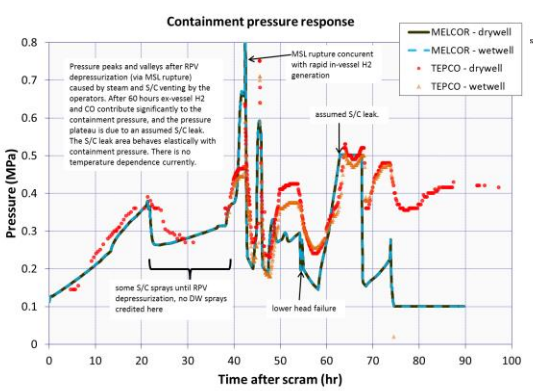
UNIT 3 ANALYSIS






RPV pressure response after HPCI stops operating
MELCOR, RPV
TEPCO data
strip chart data
assumed degraded SRV behavior: damaged SRV begins to drift below nominal setpoint
MELCOR creep rupture of MSL with failure at default creep function value of 1.0
Pressure (MPa)
Time after scram (hr)
7.8
7.7
7.6
7.5
7.4
7.3
7.2
7.1
7
6.9
6.8
36.0
37.0
38.0
39.0
40.0
41.0
42.0
43.0


In-vessel hydrogen generation
All reactions
Zirconium oxidation
Steel oxidation
Hydrogen mass (kg)
Time after scram (hr)
1400
1200
1000
800
600
400
200
0
35
40
45
50
55
60
65
70
75
80
85
90


Containment pressure response
MELCOR - drywell
MELCOR - wetwell
TEPCO - drywell
TEPCO - wetwell
Pressure peaks and valleys after RPV depressurization (via MSL rupture) caused by steam and S/C venting by the operators. After 60 hours ex-vessel H2 and CO contribute significantly to the containment pressure, and the pressure plateau is due to an assumed S/C leak. The S/C leak area behaves elastically with containment pressure. There is no temperature dependence currently.
MSL rupture concurent with rapid in-vessel H2 generation
assumed S/C leak.
some S/C sprays until RPV depressurization, no DW sprays credited here
lower head failure
Pressure (MPa)
Time after scram (hr)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
80
90
100

Unit 3 Issues

- Effectiveness of HPCI injection flow at minimum RPV pressure
- Effectiveness of drywell/wetwell sprays
- Effectiveness of Torus room flooding
- Effectiveness of emergency low pressure injection flow following RPV depressurization
- Did RPV depressurize by MSL failure or by ADS actuation

Future Work

- Ongoing baseline analyses of all three accidents (NRC)
- Uncertainty quantification study (DOE)
- Provide information to help guide decommissioning activities
- Provide information to help guide data and sample gathering during the reactor decommissioning activities

Conclusions

- The MELCOR analyses produced accident sequences that followed the general trends in the TEPCO data and observed events
- Analyses reveal important and often counter-intuitive effects
- Investment in MECOR technology over 30 years has produced a powerful tool for accident characterization and safety management
  - Inform and optimize SAMG
  - Identify and quantify unwanted side effects of actions
  - Inform and optimize hydrogen control
  - Examine multi-unit and operator effects
  - Provide greater effectiveness of Op Center Response